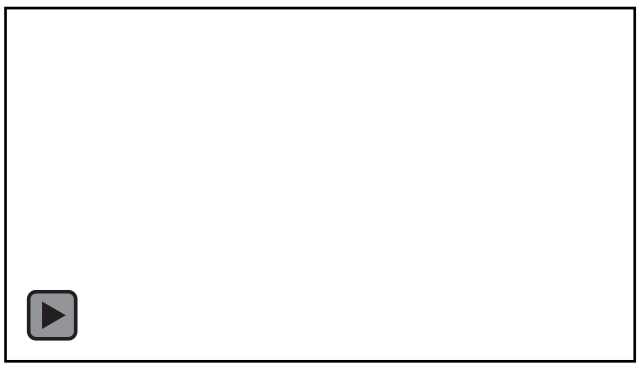
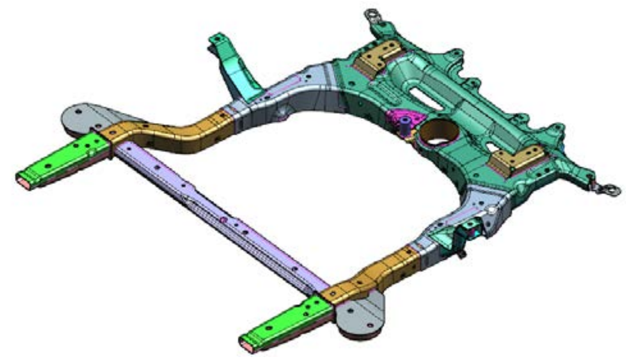
High Strength Steel-Aluminum Components by Vaporizing Foil Actuator Welding





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The Ohio State University

June 12, 2019

Project ID: MAT132

Overview

Timeline

- Start Date: October 1st 2016
- End date: September 30th 2020
- Percent complete: 50%

Targets and Barriers*

- 25% weight reduction on a 2012 mid-size sedan
- Cost premium < $5/pound saved
- Equal or better strength and durability performance
- Predictive modeling and high volume process for mixed-metal joining

*Source: 2017 U.S. Drive MTT Roadmap Report, Section 4

Budget

- Total project funding
  - DOE share: $2,405,625
  - Contractor share: $301,902
- Funding FY 2018: $770,411
  - $688,796 DOE, $81,615 Contractor
- Funding FY 2019: $956,357
  - $854,031 DOE, $102,325 Contractor

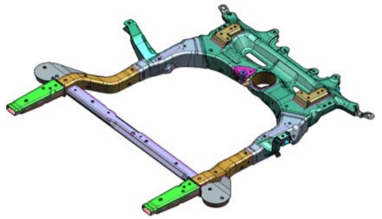
Partners

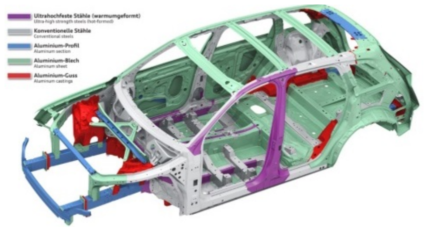
- OSU (Lead)
- Magna
- PNNL
- Coldwater Machine Company
- Ashland
- Arconic
- Hydro (SAPA extrusions)

Relevance/Objectives

- Objective:
  - *Proposed* 20% weight reduction of a current all-steel automotive component from a 2016 mid-size sedan at a cost premium of $3/lb saved by developing a mixed-material joining technology capable of high-volume production
  - The produced component should meet or exceed strength and durability of incumbent component
  - Have a predictive modeling capability for relating process, structure and property of joints
- Project directly addresses the listed barriers and targets

- Impact:
  - ➢ This project accelerates and focuses the development of vaporizing foil actuator for production of an automotive component. At project completion, the technology will be ready for adoption within the research and development groups of Tier 1 and OEM for assembly of any mixed/advanced material bodies

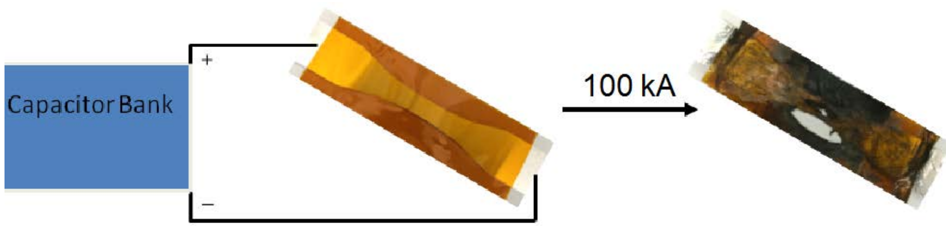


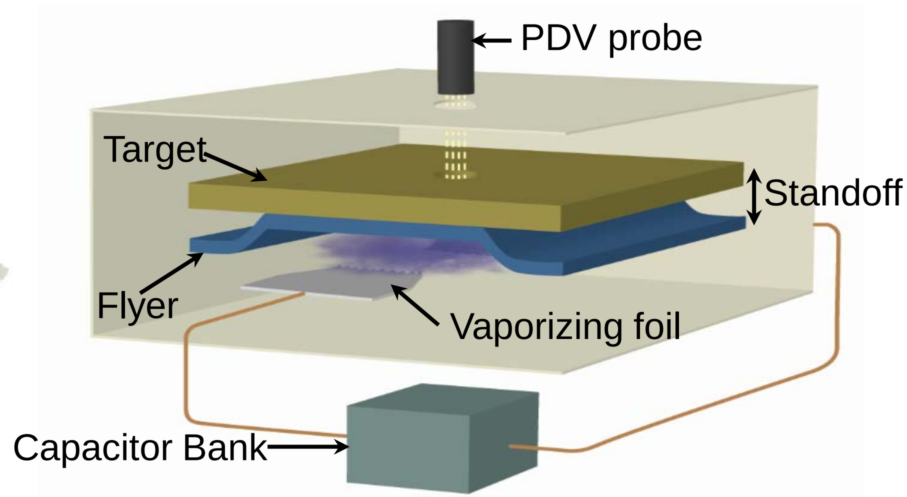


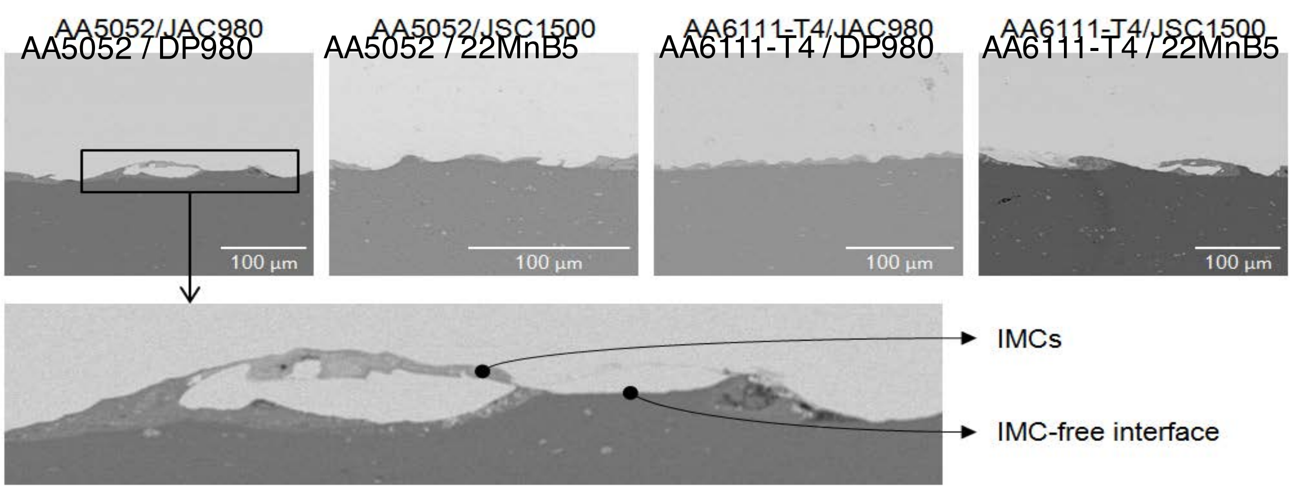
Approach – impact welding

Solid-state impact welding of aluminum to steel

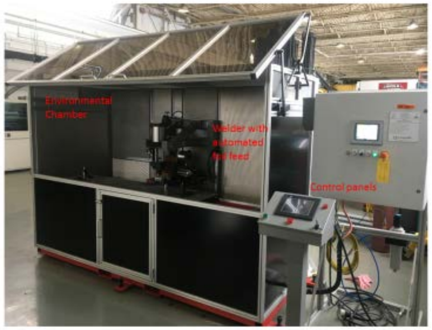
- nominal 500 m/s, 20° impact provides weld.



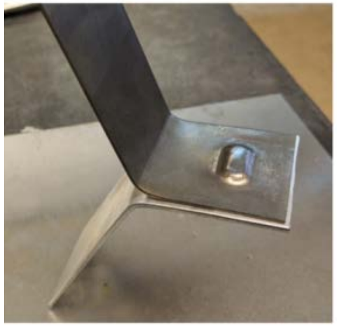




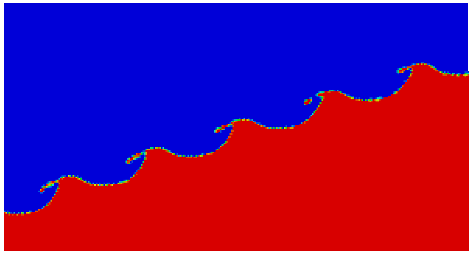
Approach



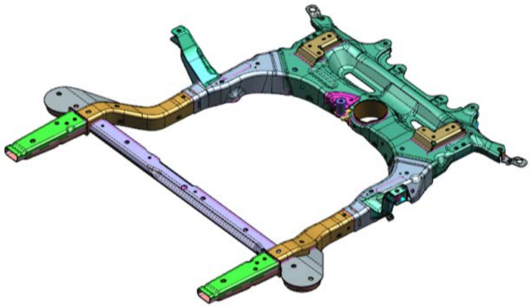
Process & tool development

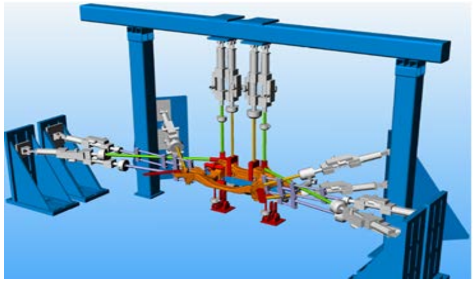


Welding and testing Coupons



Microstructure Characterization and Modeling





Prototype build and durability testing

Approach/Technical Plan

Major tasks	Oct 2016 – Sept 2017	Oct 2017 – Sept 2018	Oct 2018 – Sept 2019	Oct 2019 – Sept 2020
Coupon scale pre-screening				
Numerical model development and validation				
Coupon scale testing of down-selected material pairs				
Design for manufacturing of prototype component				
Production and testing of prototype components				
Design and build of robotic welding system				

★ **Go/No-Go Milestones**

Budget Period 1: Three material clear down-selection criteria: (i) parent material failure during pry testing (ii)weld strength > 70% of weaker parent material (iii) post-corrosion strength > 80% of pre-corrosion strength

Budget Period 2: Release of prototype design that meets baseline requirement for strength, stiffness and durability

Budget Period 3: Strength and durability of prototype component equal to or better than baseline component

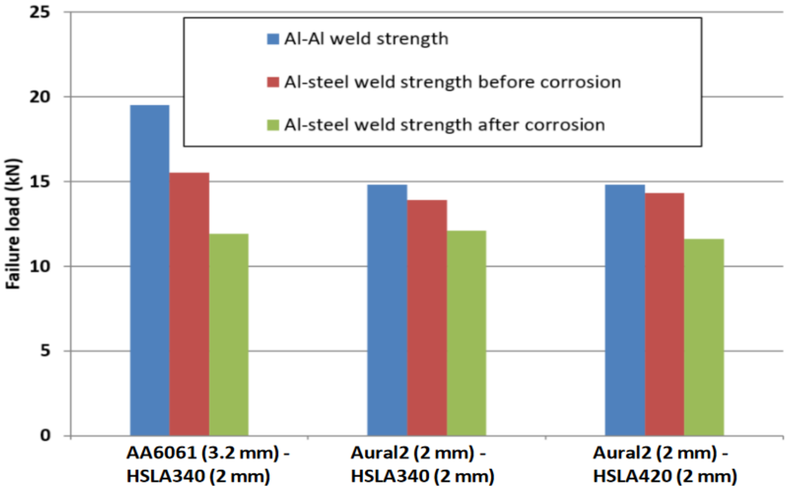
Approach/Milestones

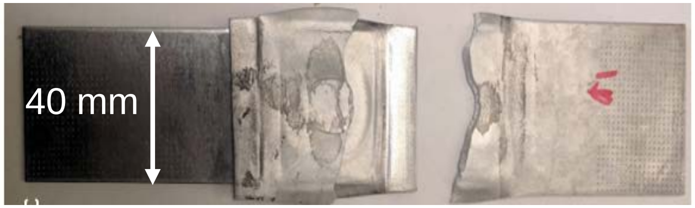
Task No	Task title	Milestone type	Milestone number	Milestone description	Milestone verification process	Anticipated date	Anticipated quarter
1.1	Coupon scale pre-screening		1.1.1	6 material systems selected for preliminary investigation	Benchmarking	M3	1
			1.1.2	Pedestal system integration complete	Demonstration	M6	2
			1.1.3	Weld interface with IMC thickness <2µm obtained	SEM	M9	3
		Go/No-Go	1.1.4	Three material systems clear the threshold for further testing (parent material failure during testing)	Mechanical testing	M12	4
1.2	Modeling		1.2.1	The range for appropriate welding angles recommended	Comparison to experiment	M6	3
2.1	Further coupon test		2.1.1	High cycle fatigue limits are >30% of static yield strength of the coupons	ASTM tests	M18	6
2.2	Model validation		2.2.1	Predicted wavelength and amplitude within 80% of experiments	SEM	M21	7
			2.2.2	Predicted strength within 90% of experiments	Comparison to experiment	M24	8
2.3	Design of prototype		2.3.1	Math data and load profile for baseline cradle design ported into the new design	Data supplied by OEM and used by Magna	M15	5
		Go/No-Go	2.3.2	Release of prototype design and its CAE performance	Compared to baseline	M24	8
3.1	Production and testing of prototype		3.1.1	25 sets of subcomponents produced	Actual production	M27	9
			3.1.2	Prototype assembly fixtures built	Demonstration	M30	10
		Go/No-Go	3.1.3	Ten prototypes assembled	Actual production	M32	11
			3.1.4	Static and dynamic loads exceed all-steel design	Mechanical testing	M34	12
			3.1.5	CAE predictions within 90% of the physical tests	Comparison to prototype tests	M35	12
3.2	Robotic VFAW		3.2.1	Design of robotic VFAW system released	Design shared with Magna	M36	12

Complete In Progress Not started

FY17 Summary: Screening and Selection of Baseline Component

- 5 out of 8 welded pairs tested had base metal failure
- >70% joint efficiency for 3 material pairs
- >80% strength retention after corrosion for those pairs





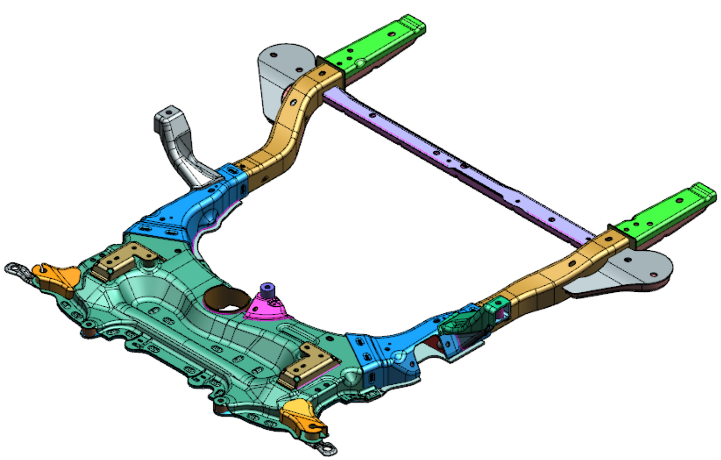
HSLA 340-Aural 2 (3.3mm)

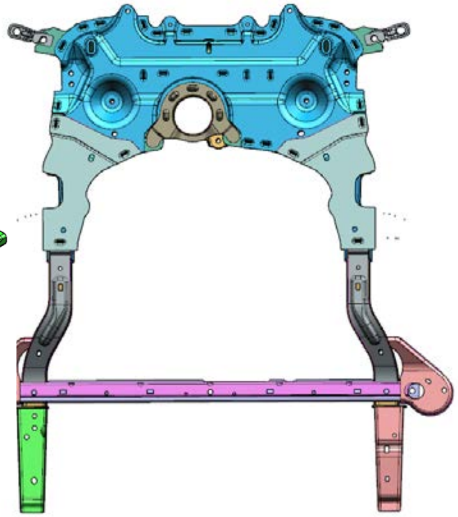
- 2016 Chevrolet Cruze
- Global/US Volume: 600,000/250,000 (US) per year
- 24.4 kg (all-steel) -> 19.5 kg (target hybrid with 20% weight reduction)
- With aluminum front end, estimated weight: 18.5 kgs
- Design based on AA5754 (4mm thick) stampings joined to HSLA 340 steel

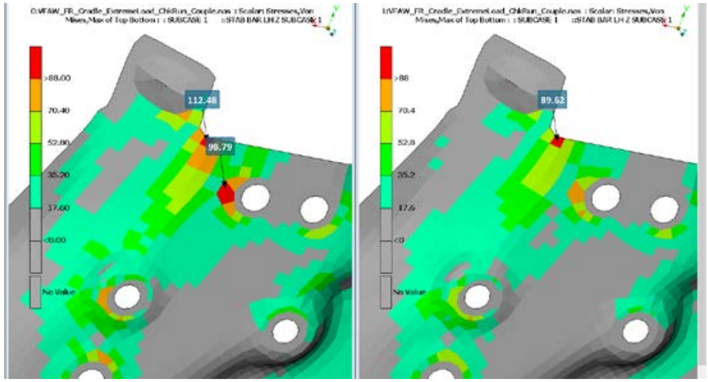
Technical Accomplishment:

Prototype design complete: **Go**/No-Go

- Assembly sequenced with MIG welding of steel parts and VFAW of mixed regions. 46 subcomponents, >50 VFA welds
- Uses 4mm thick AA5754-O. Modeling with lower thickness raised stiffness and yielding concerns
- Final design weight: 21.6kg (12% reduction)
- Alternative aluminum-intensive designs can reduce weight by >20%



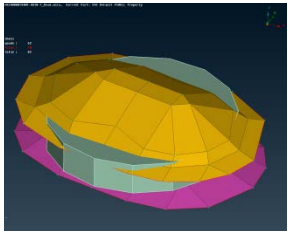
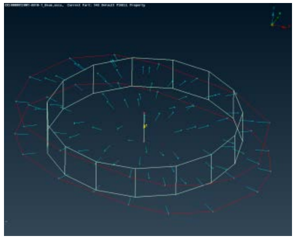




3mmt Al 4mmt Al

Technical Accomplishment:
Prototype design: static section force on VFAW

- Extreme (abuse) loading condition modeled with Nastran and ABAQUS
- Max force on a weld= **2.5 kN** with extreme loading at Front Lower Control Arm (FLCA) location

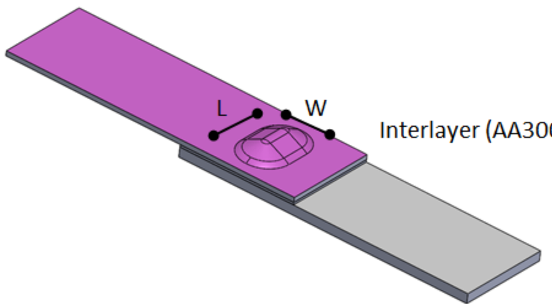
Nastran static method

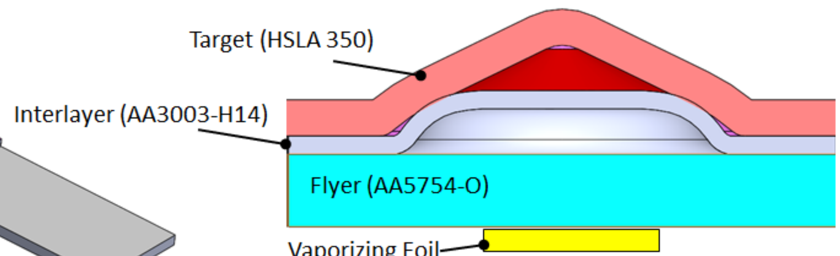
Technical Accomplishment:

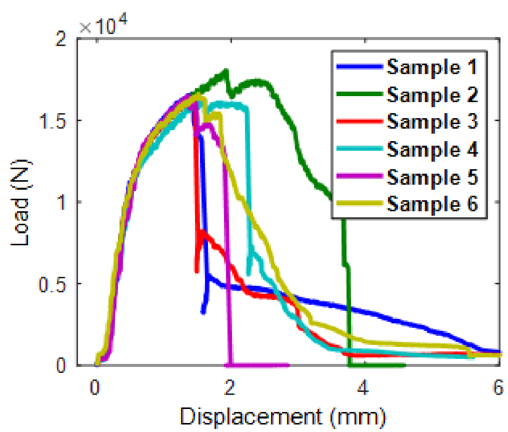
Instrumented testing of selected pair with pre-formed configuration

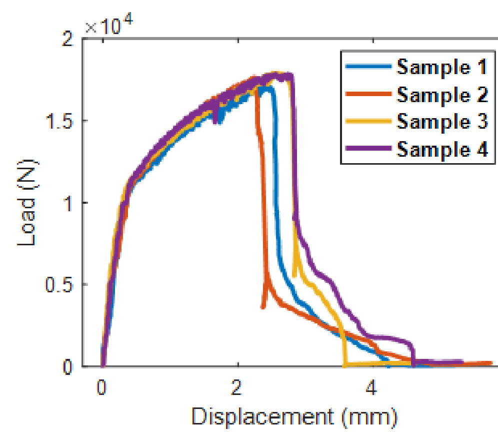
- Pre-form and foil designs finalized
- Shear failure load > 16kN obtained
- Weld strength matches interlayer material (AA3003)

cross head motion perpendicular to the longer dimension of the weld









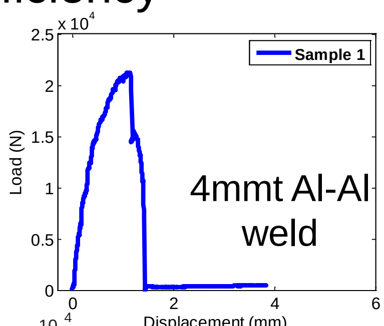
HSLA 340-AA5754-O (3.3mm)

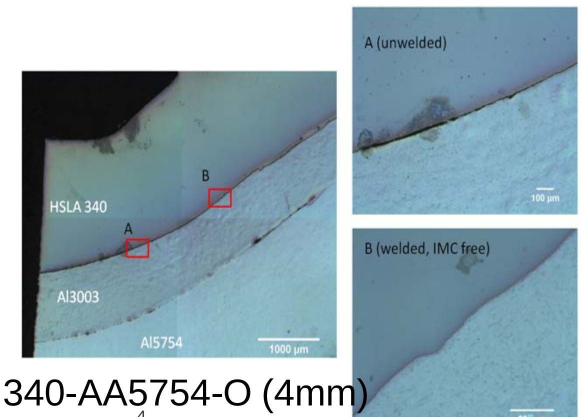
cross head motion parallel to the longer dimension of the weld

Technical Accomplishment:

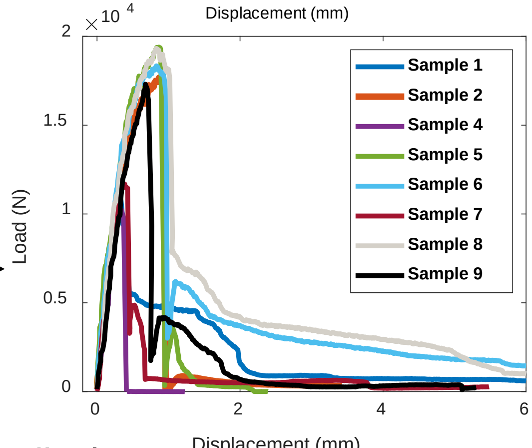
Instrumented testing of selected pair with pre-formed configuration

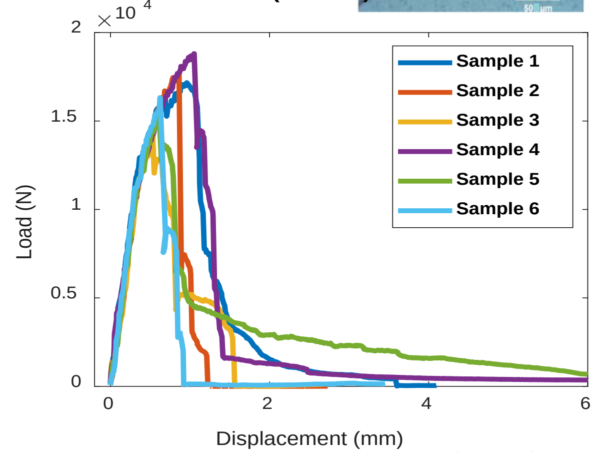
- 4mm thick AA5754-O to be used for prototype component
- Al-Fe interface had discontinuous intermetallic compounds
- Cured adhesive around weld
- >80% joint efficiency





HSLA 340-AA5754-O (4mm)





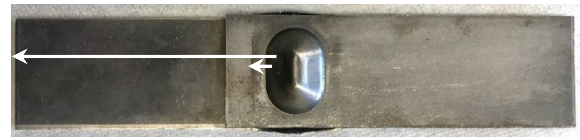
cross head motion perpendicular to the longer dimension of the weld

cross head motion parallel to the longer dimension of the weld

Technical Accomplishment:

Fatigue testing at high, medium and low cycles

- 100% load = 16.55 kN
- Tension-tension tests
- Cured adhesive around weld
- High cycle fatigue limit >30% of static strength

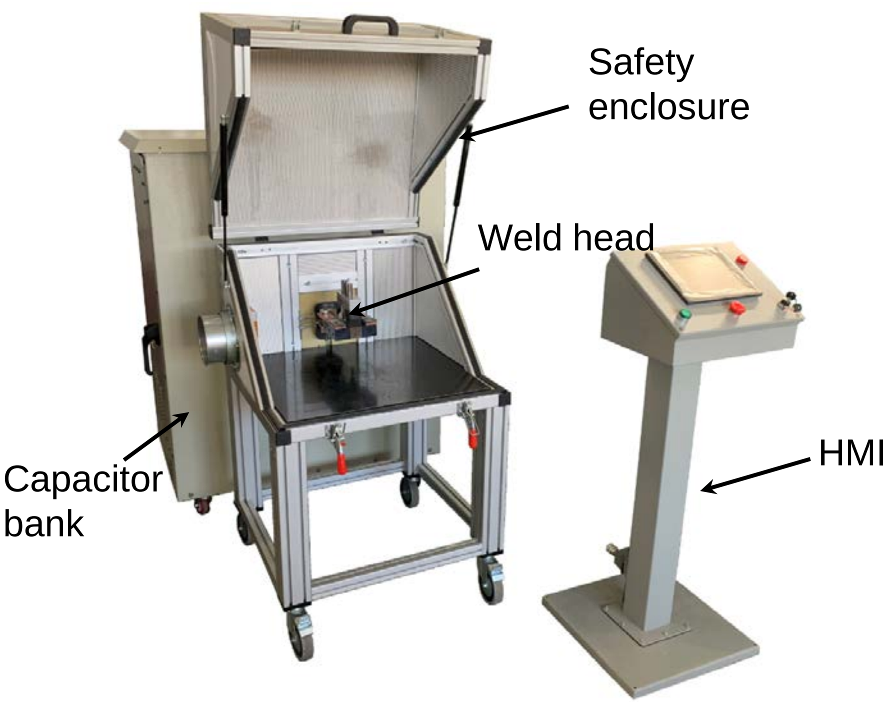


Load	Sample	Cycle at failure
4-40%	1	1146961
	2	486423
	3	935927
	4*	(759203 +) 2528637
	5	987120
4.2%-42%	1	850000
4-50%	1	74603
	2	59669
	3	93479
	4	123810
	5	49537
4-60%	1	29240
	2	10865
	3	30421
	4	29213
	5	14950
	6	18724

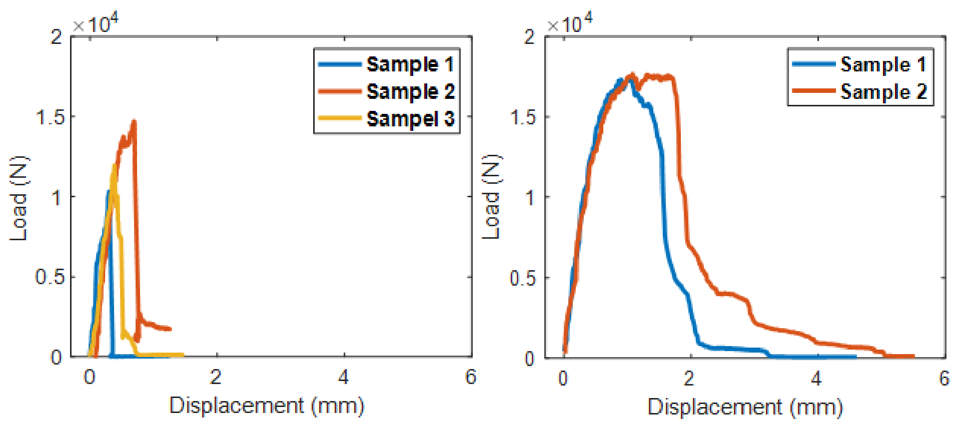
* Stopped at 759,203 cycles and was restarted

Technical Accomplishment:
Fast capacitor bank fabricated and tested

- 2x faster discharge than existing capacitor bank
- HSLA 340-AA5754-O welds made with 25% less energy. Used for making most of the welds in FY18
- A system set up at a welder training school (RAMTEC) in Marion, OH
- To be set up at Magna for prototype assembly



2.2mm HSLA 350 welded to 4mm AA5754-O

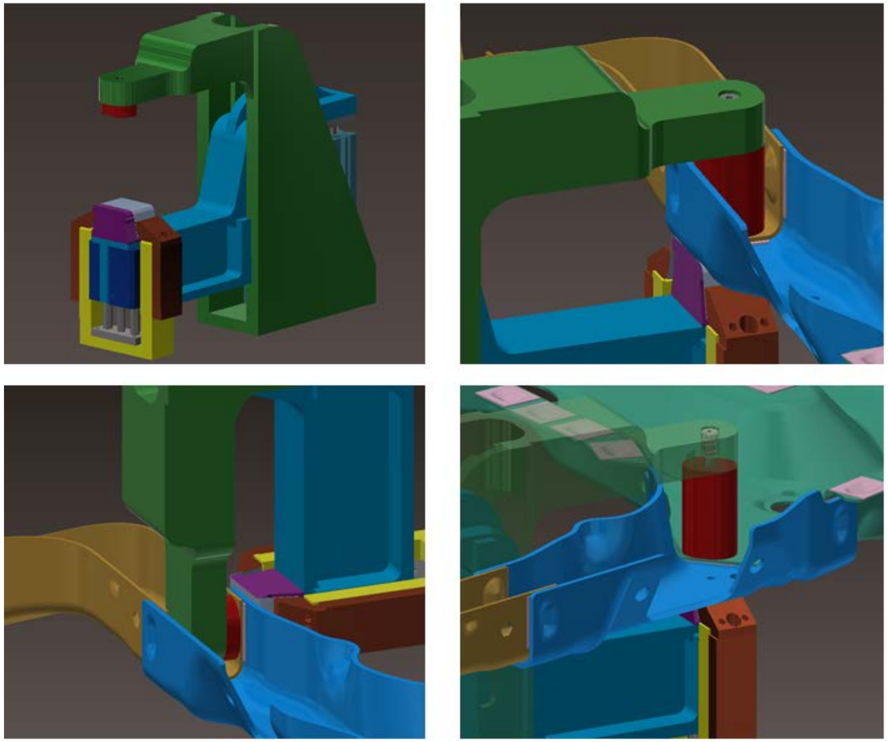


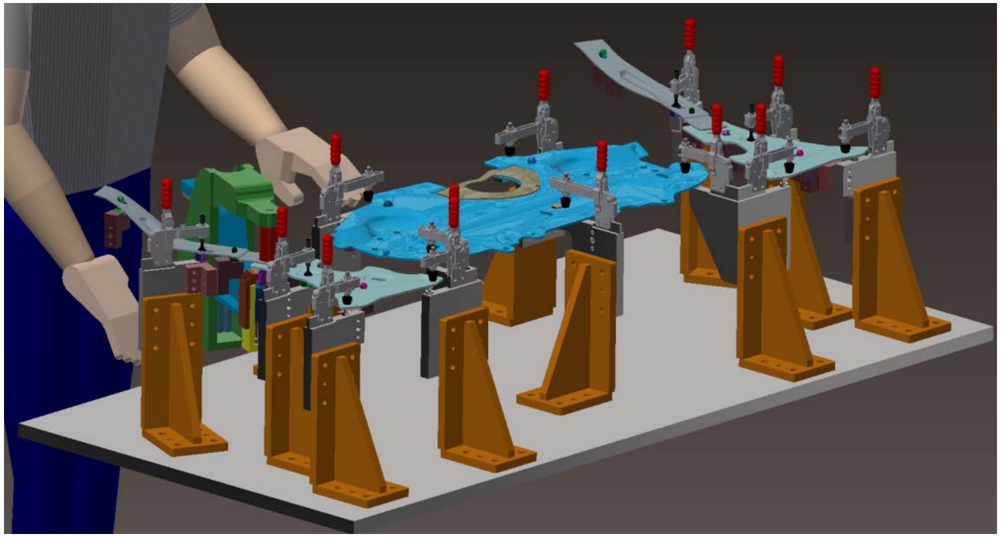
6 kJ on old bank

4.2 kJ on new bank

Technical Accomplishment:
Design of prototype weld head and VFAW fixtures

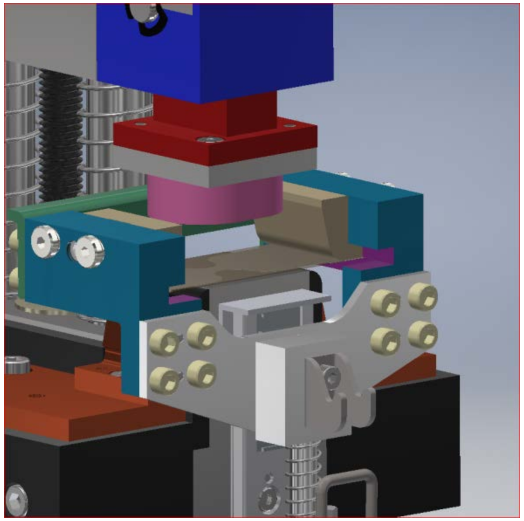
- Capable of welding in all configurations
- Quick change of anvil and breech blocks as needed
- Pneumatic clamping of workpiece and foil actuator



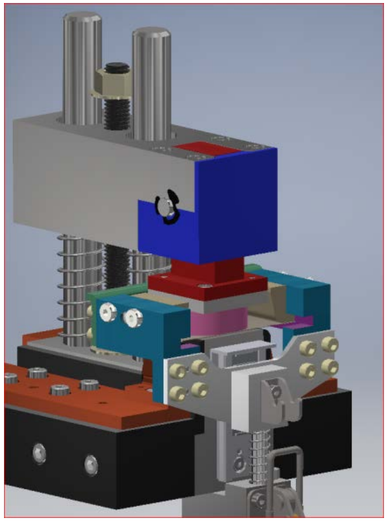


Technical Accomplishment:
Accurate foil placement and force estimation

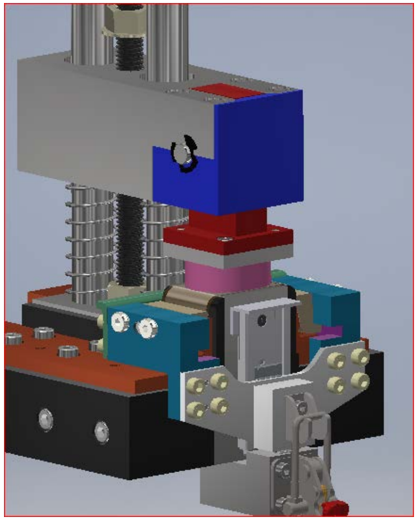
- Validation prototype weld head. Step-by-step foil placement method shown below
- Shear pins of various diameter used to estimate the “kick” from the foil vaporization
- Information useful for designing equipment



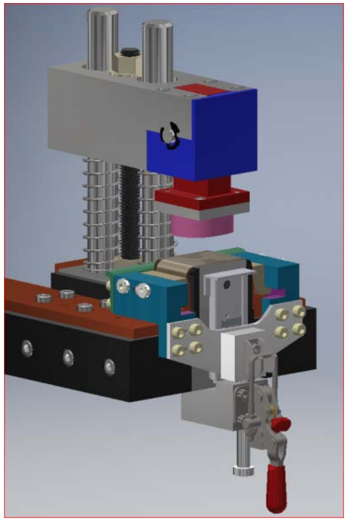
Foil ready



Foil clamped by anvil



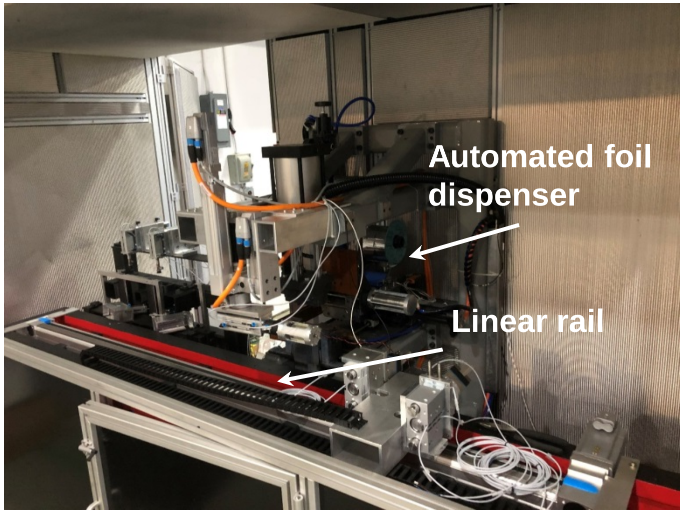
Foil clamped with electrode

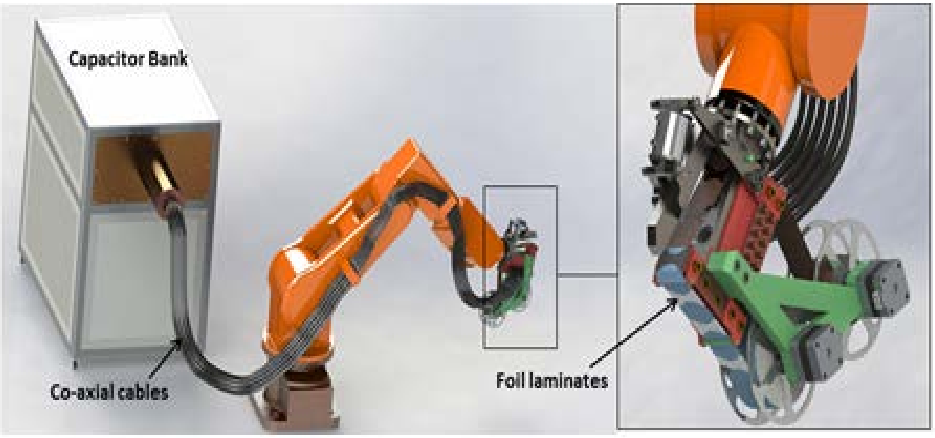


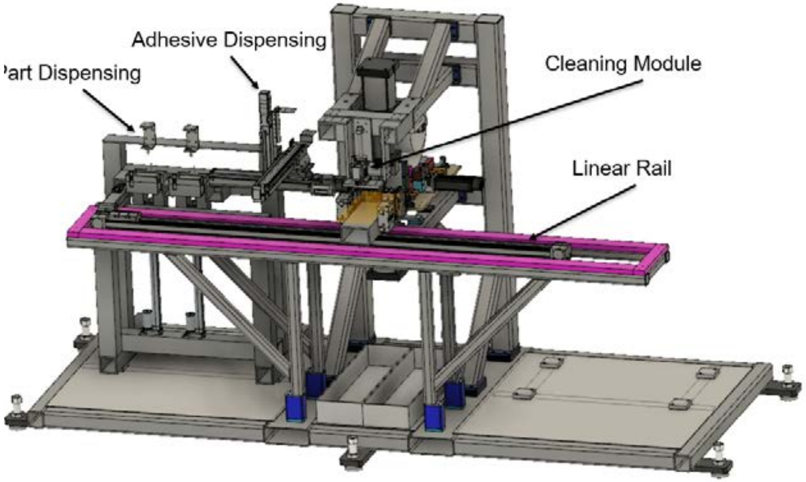
Anvil released Head ready for workpiece

Process Automation

- Pivot from articulated arm robot mounted weld head to fully automated pedestal welder
- System is designed around being able to do hundreds of lap shear samples with no human intervention
- The system will have part feeding, adhesive dispensing, VFA welding, and cleaning after the weld
- Anticipated to be running mid 2019

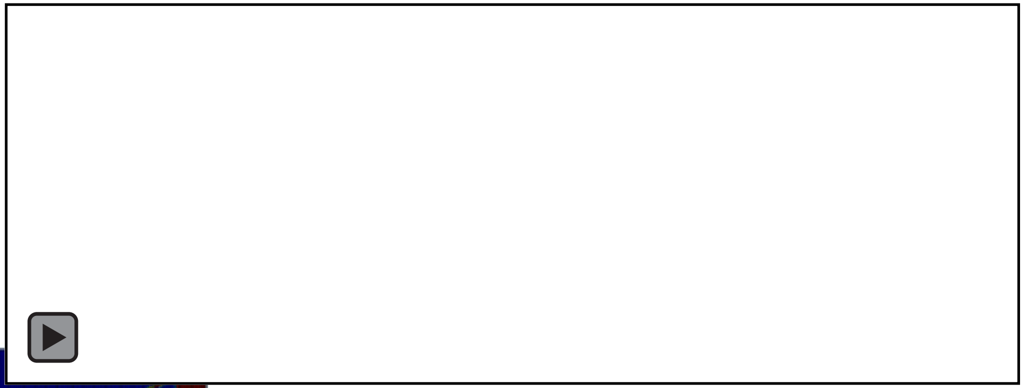


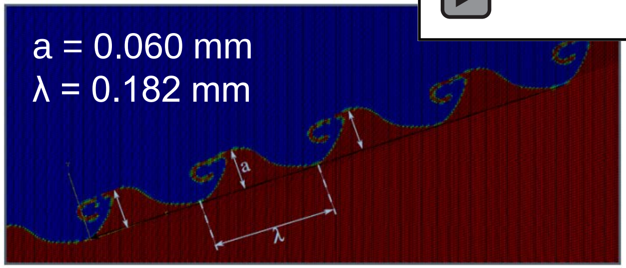


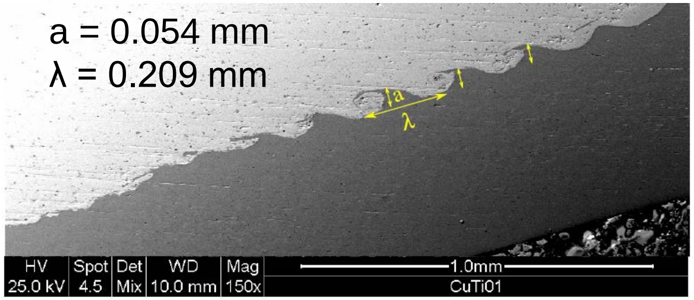


Technical Accomplishment:
Validated Process-Structure Computational Model

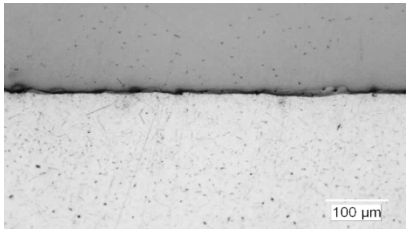
- Validated Process-Structure model: Quantitatively capturing interfacial characteristics, jetting and temperature.







Copper-Titanium

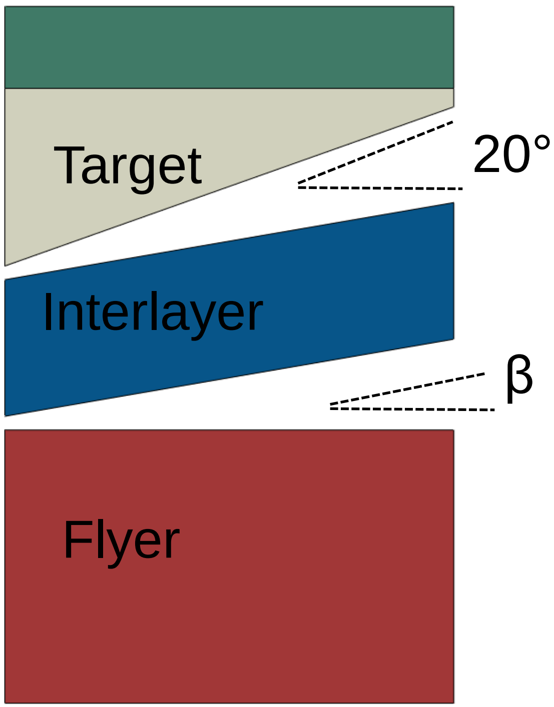


Steel-Aluminum

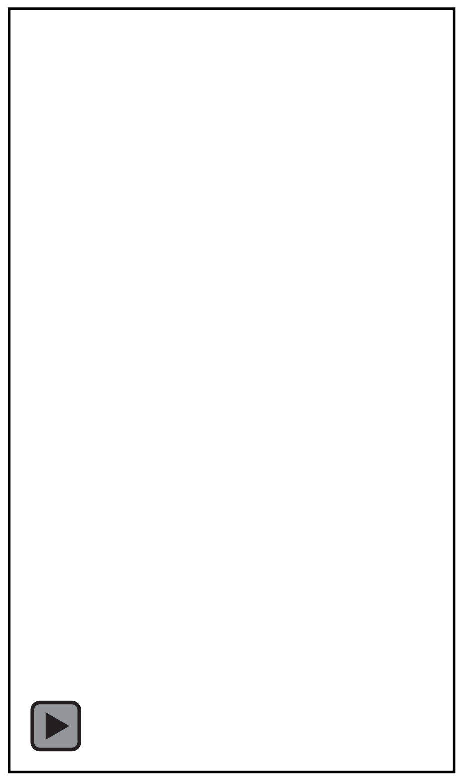
[Gupta et al, JMPT, 2018]

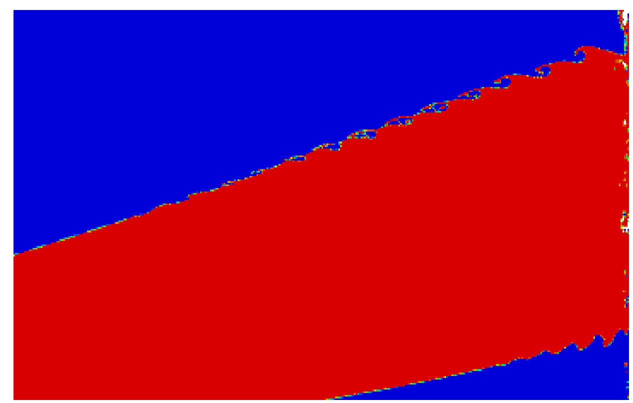
Technical Accomplishment:

Process-Structure linkage in impact welding with interlayer



- In the case of welds with interlayer, the overall quality of welds is dependent on two interfaces
- Representative simulations: Target was kept at 20° and β was varied (0°, 5°, 10°)

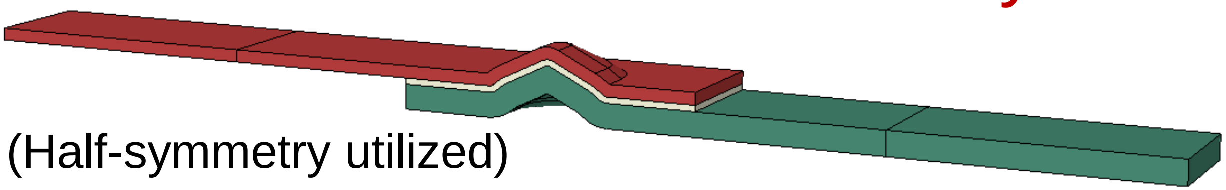




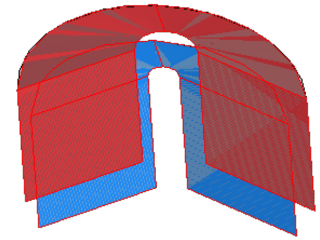
- β = 10° predicted the desired wavy interfacial morphology

Technical Accomplishment:

Structure-property linkage in impact welding with interlayer

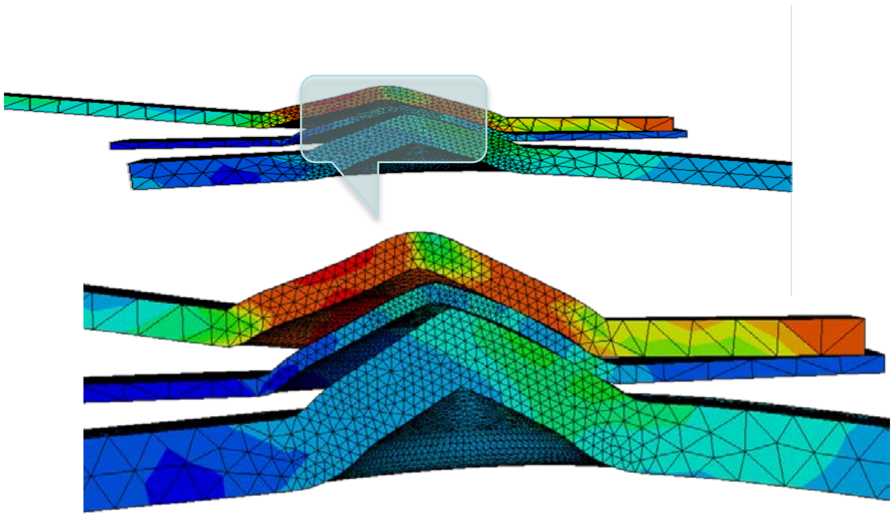


(Half-symmetry utilized)

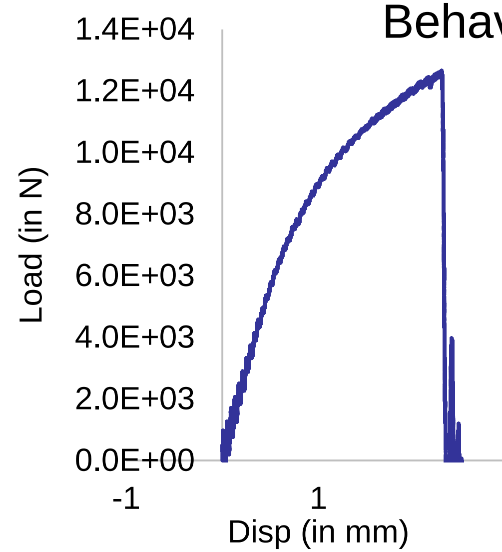


Welded Surfaces (Cohesive interfaces)

Deformation behavior



Load-Displacement Behavior



- Several model parameters at both interfaces need to be obtained from different mechanical characterization tests

Responses to Previous Year Reviewers' Comments

- Bit of concern with the delay of the prototype design, supporting CAE results, and the impact it could have on the timely finish of the project.

The project is delayed by 3 months, but now the prototype design and related CAE are complete. By getting an early start on automation task, we hope to finish the overall project in time

- Include activities at coupon or component level for the sensitivities in bond gap, and the necessary control of bond gap to achieve optimum joint strength performance.

Foil-workpiece stack up (referred to as bond gap above) appears to have significant effect on joint strength as shown by some testing performed this year. Going forward, better control will be afforded by the validation prototype and the prototype weld heads fabricated for coupon and component level welding

- It would be good to also have a real component testing planned rather than sticking to sub-component testing.

The assembled prototype component will be tested at the end of FY19 or beginning of FY20

Collaboration and Coordination

- **OSU's Impulse Manufacturing Lab, Fontana Corrosion Center, CDME:** Facilities and expertise for impact welding, process development, standard corrosion testing at coupon and subcomponent level in addition to program management
- **Magna (Sub):** CAD, CAE, prototype build and testing
- **Coldwater Machine Company (Sub):** equipment builder and system integrator
- **PNNL:** Numerical simulation of impact welding process, interfacial wavy pattern and jetting, and mechanical performance of the welded coupons
- **Ashland:** Supplies structural adhesives for galvanic corrosion protection. Also provides in-house testing
- **Arconic:** Supplies 5xxx and 6xxx sheets for screening tests and prototype build
- **Hydro:** Supplies 6xxx and 7xxx grade aluminum extrusions for possible chassis and body side applications

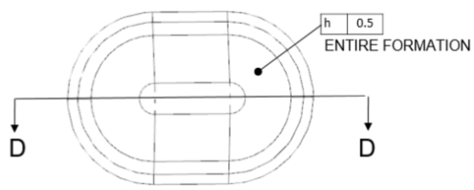
Remaining Challenges and Barriers

- Prototype scale assembly
- Control of extraneous deformation outside weld region
- Weld cycle time
- Adhesive needs to be cured prior to welding
- Stack up tolerance to be determined
- Tool and equipment life
- Standard data package for design with VFAW

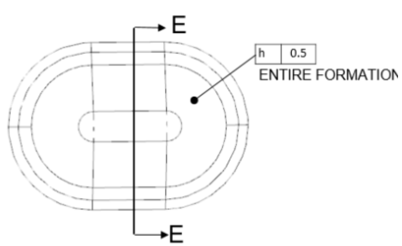
Proposed Future Work

- Validation of prototype weld heads with coupon scale welding
- Understanding of stack up gap and misalignment tolerances
- Set up of work cell at Magna
- Component assembly and testing
- Testing of fully automated pedestal welding system
- Complete the structure property modeling of 3-layer welds

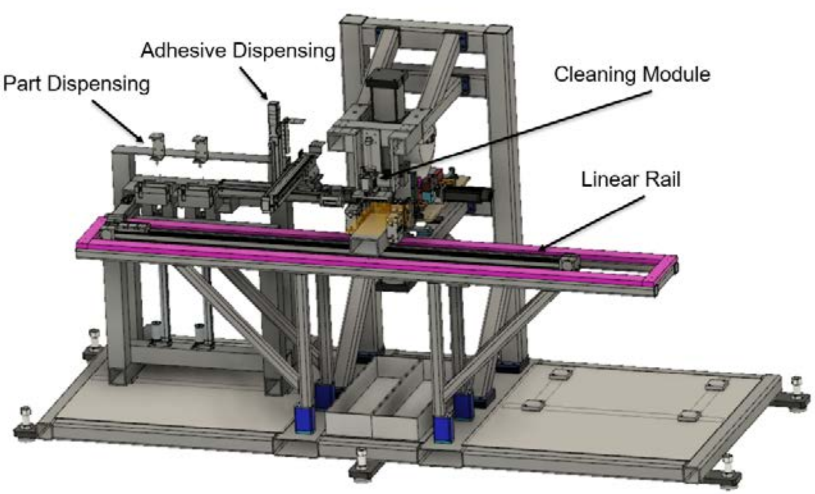
*Any proposed future work is subject to change based on funding levels

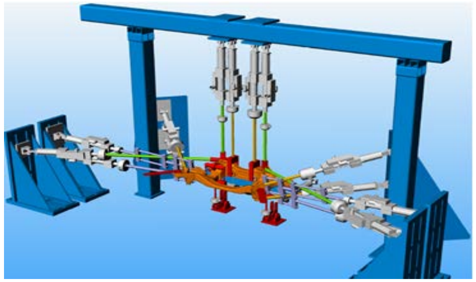


DETAIL A



DETAIL B





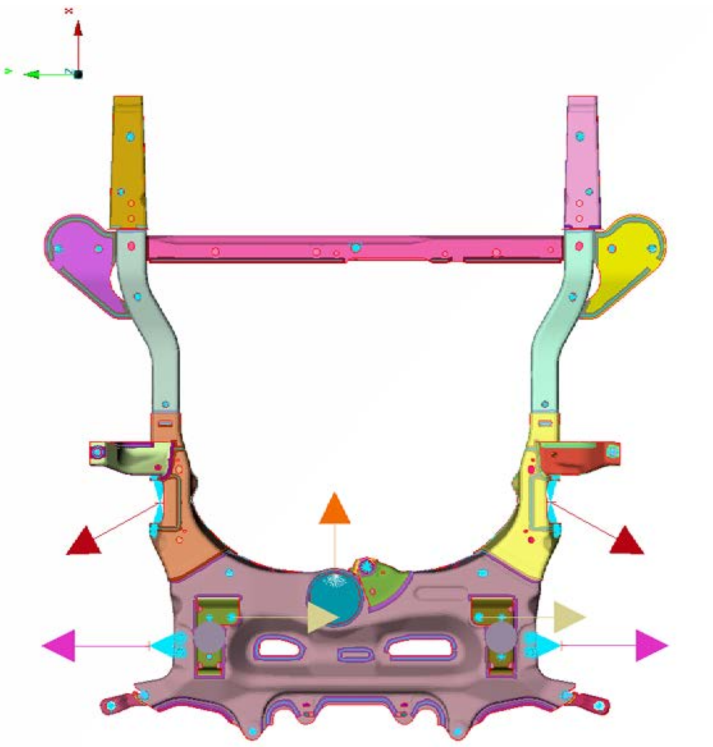
Summary

- Vaporizing Foil Actuator Welding (VFAW) has been shown to successfully weld stamping grade aluminum and steel pair in aluminum thickness (4mm) relevant to sub-frame structures
- The welds are strong and have a load bearing capacity greater than 70% of an aluminum-aluminum weld of the same geometry
- The mixed-material prototype component is going to be 12% lighter than the all-steel baseline. The lower weight reduction target enables more rigorous testing of the manufacturability of VFAW given that more than 50 welds are to be made in each component
- Computer aided engineering-based requirements for weld strength and durability are met by coupon scale test data
- Coupon scale testing of the welds demonstrated high cycle fatigue (>1M cycles before failure) at 40% of their static strength
- A validated process-structure model is now available for simulating impact welding processes. The structure-property model needs more validation data
- FY 2019 work is focused on transitioning the technology for component level assembly and automation

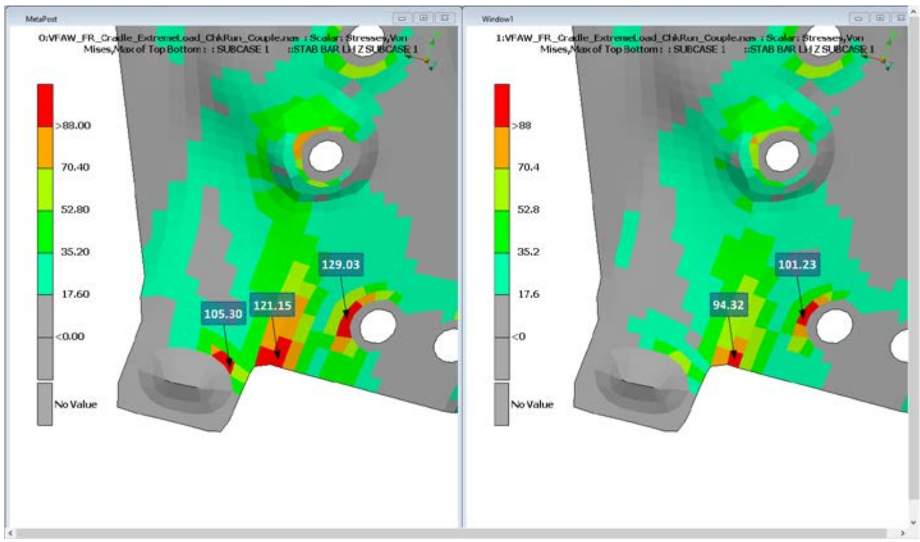
Technical Back-Up Slides

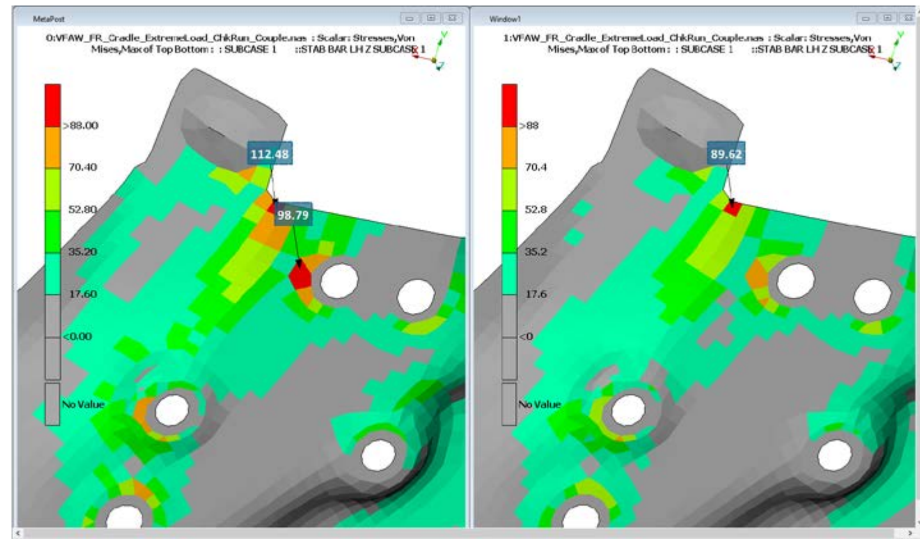
Load cases

- **Scope**
  - Evaluate the section force on VFAW design and evaluate the durability performance for DRQ 3965
- **Model Content**
  - DRQ 3965 Front Cradle
- **Material**
  - Steel and steel welding
  - Aluminum and VFAW
  - No fatigue material for aluminum in this design
- **Method**
  - Nastran static stress check
  - Check 88Mpa yield stress on aluminum
  - Check 50ksi yield stress on steel
- **Boundary Condition**
  - Force as shown
  - 1-3 DOF at body mount



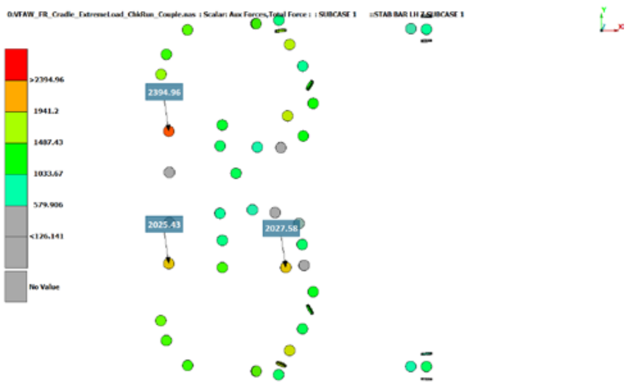
Max stress with 3mmt and 4mmt Al

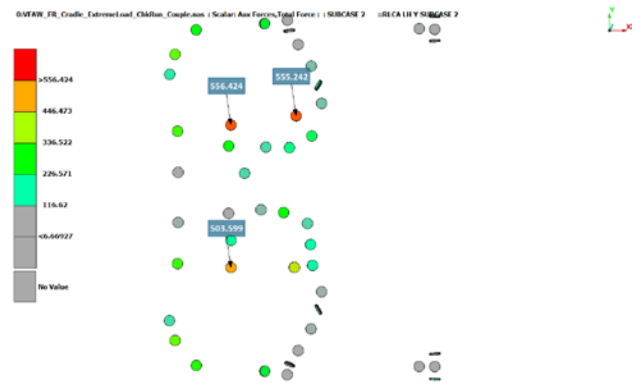


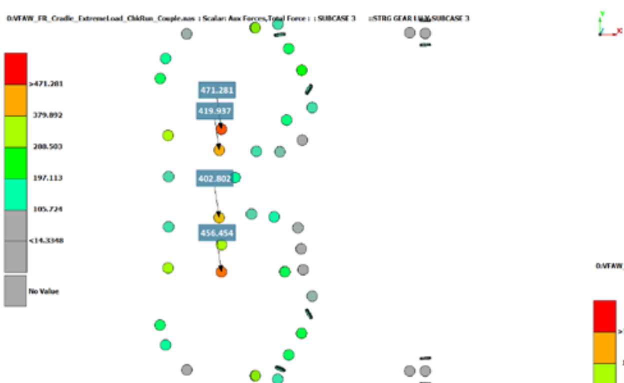


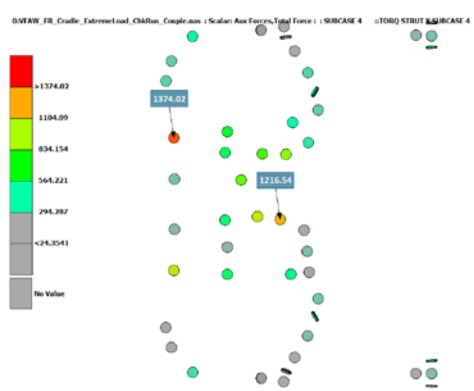
- Check max stress on the bottom aluminum sheet
- The radius corner would be a concern for the 3mm thickness design

Max force on joint





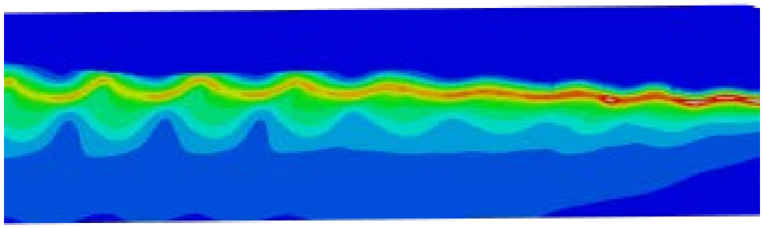


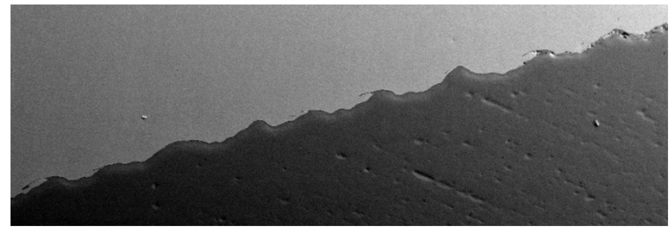


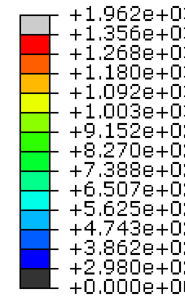
Temperature predictions

Impact angle, β =20°

585 m/s







860 m/s